NREL/TP-540-43543
ORNL/TM-2008/117

Energy Efficiency and Renewable Energy

EFFECTS OF INTERMEDIATE ETHANOL BLENDS ON LEGACY VEHICLES AND SMALL NON-ROAD ENGINES, REPORT 1

Brian West,* Keith Knoll,† Wendy Clark,† Ronald Graves,* John Orban,‡
Steve Przesmitzki,† and Timothy Theiss*

*Oak Ridge National Laboratory, Oak Ridge, Tennessee
†National Renewable Energy Laboratory, Golden, Colorado
‡Battelle Memorial Institute, Columbus, Ohio

Date Published: October 2008

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

EXECUTIVE SUMMARY

E.1 IMPACT OF INTERMEDIATE ETHANOL BLENDS ON LEGACY VEHICLES AND ENGINES

In summer 2007, the U.S. Department of Energy (DOE) initiated a test program to evaluate the potential impacts of intermediate ethanol blends on legacy vehicles and other engines.* The purpose of the test program is to assess the viability of using intermediate blends as a contributor to meeting national goals in the use of renewable fuels. Through a wide range of experimental activities, DOE is evaluating the effects of E15 and E20—gasoline blended with 15 and 20% ethanol—on tailpipe and evaporative emissions, catalyst and engine durability, vehicle driveability, engine operability, and vehicle and engine materials.

This first report provides the results available to date from the first stages of a much larger overall test program. Results from additional projects that are currently underway or in the planning stages are not included in this first report. The purpose of this initial study was to quickly investigate the effects of adding up to 20% ethanol to gasoline on the following.

- Regulated tailpipe emissions for 13 popular late model vehicles on a drive cycle similar to real-world driving and 28 small non-road engines (SNREs)† under certification or typical in-use procedures.
- Exhaust and catalyst temperatures of the same vehicles under more severe conditions.
- Temperature of key engine components of the same SNREs under certification or typical in-use conditions.
- Observable operational issues with either the vehicles or SNREs during the course of testing.

As discussed in the concluding section of this report, a wide range of additional studies are underway or planned to consider the effects of intermediate ethanol blends on materials, emissions, durability, and driveability of vehicles, as well as impacts on a wider range of non-automotive engines, including marine applications, snowmobiles, and motorcycles.

Section 1 (Introduction) gives background on the test program and describes collaborations with industry and agencies to date. Section 2 (Experimental Setup) provides details concerning test fuels, vehicle and SNRE selection, and test methods used to conduct the studies presented in this report. Section 3 (Results and Discussion) summarizes the vehicle and SNRE studies and presents data from testing completed to date. Section 4 (Next Steps) describes planned future activities. The appendixes provide test procedure details, vehicle and SNRE emissions standards, analysis details, and additional data and tables from vehicle and SNRE tests.

E.2 BACKGROUND

The Energy Independence and Security Act of 2007 calls on the nation to significantly increase its use of renewable fuels to meet its transportation energy needs. The law expands the renewable fuel standard (RFS) to require use of 36 billion gallons of renewable fuel by 2022. Given that ethanol is the most widely used renewable fuel in the U.S. market, ethanol will likely make up a significant portion of the 36-billion-gallon requirement.

---

*The test program is co-led and funded by the DOE Office of Energy Efficiency and Renewable Energy (EERE) Biomass Program and the EERE Vehicle Technologies Program with technical support from the Oak Ridge National Laboratory and the National Renewable Energy Laboratory. DOE and the laboratory team have worked closely with representatives from the U.S. Environmental Protection Agency, U.S. auto manufacturers, engine companies, and other organizations to develop and conduct a robust test program.

† Ten different equipment models were tested, with multiple copies tested in some cases for a total of 28 engines.

The vast majority of ethanol used in the United States is blended with gasoline to create E10—gasoline with up to 10% ethanol. The remaining ethanol is sold in the form of E85—a gasoline blend with as much as 85% ethanol that can only be used in flexible-fuel vehicles (FFVs). Consumption of E85 is currently limited by both the size of the flex-fuel vehicle fleet and the number of E85 fueling stations.

Given projected growth in ethanol production and the new RFS, most analysts agree that the E10 market will be saturated in the next few years, possibly as soon as 2010. Although DOE remains committed to expanding the E85 infrastructure, that market represented less than 1% of the ethanol consumed in 2007 and will not be able to absorb projected volumes of ethanol in the near-term. Given this reality, DOE and others have begun assessing the viability of using intermediate ethanol blends as a way to accommodate growing volumes of ethanol.

E.3 DEVELOPMENT OF TEST PROGRAM

The DOE team [DOE, the National Renewable Energy Laboratory (NREL), and the Oak Ridge National Laboratory (ORNL)] has collaborated with industry and other experts regarding the development and implementation of the test program. A number of automotive and non-road engine manufacturers provided significant input into the test protocols. This collaboration was typically coordinated through industry organizations such as the U.S. Council for Automotive Research, the Coordinating Research Council (CRC), the Outdoor Power Equipment Institute, the Alliance of Automobile Manufacturers, and the Association of International Automobile Manufacturers. Staff at the U.S. Environmental Protection Agency (EPA) provided important guidance in helping DOE design tests and select sample vehicles and small engines based on sales volumes and related test programs. In addition, statistical experts at Battelle Memorial Institute assisted in the vehicle selection process and data analysis. Argonne National Laboratory also assisted in data collection. DOE expects to continue to work closely with industry on ongoing and future tests.

Close interactions with representatives from the affected industries and EPA have been particularly helpful in refining or developing test protocols to assess the impact of intermediate ethanol blends on the equipment being tested. With respect to the specific studies presented in this report, standard test procedures were used where possible, but in many cases, test protocols had to be modified or created where they did not yet exist.

E.4 SUMMARY OF VEHICLE TESTS AND DATA

For the studies documented in this report, vehicles were selected based on manufacturer, engine configuration and displacement, emission control system evolution, and model year. An initial group of 11 vehicles was selected primarily to span evolution in emission control system technology and focused on two model years, 2003 and 2007. Five additional popular model vehicles were selected from a set of vehicles identified by CRC as particularly likely to be sensitive to increased ethanol content in gasoline.* These five vehicles included three 1999 models, one 2001 model, and one 2004 model. All of the vehicles were tested on federal certification gasoline (E0), E10, E15, and E20—that is, gasoline and three different gasoline/ethanol blends. Due to time constraints in obtaining match-blended fuels, splash blends were used in this study—that is, the E0 certification fuel was simply diluted with appropriate amounts of fuel grade ethanol. Match-blended and splash-blended fuels have different hydrocarbon and volatility characteristics. While the different fuel characteristics were not

*The CRC Emissions Committee identified several vehicles suspected of not applying long-term fuel trim under high-load, open-loop conditions (http://www.crcao.com/doingbusiness/recentRFP.html, CRC Project No. E-87-1). Further details are in Sect. 2.2.1.1.

expected to have significant impact on the temperature measurements, the emissions results may have been influenced slightly due to unintended changes in the vehicle cold start and warm up. The effect of different fuel characteristics on vehicle tailpipe emissions is currently being examined in a separate DOE–EPA jointly sponsored project.

This first report provides data from testing completed to date on 13 of the 16 vehicles. Results from the remaining 3 vehicles and additional analysis from the 16-vehicle set will be included in the second report, expected in January 2009.

E.4.1 Fuel Economy

- All 13 vehicles exhibited a loss in fuel economy commensurate with the energy density of the fuel.* With E20, the average reduction in fuel economy (i.e., the reduction in miles per gallon) was 7.7 percent compared to E0.
- Limited evaluations of fuel with as much as 30% ethanol were conducted, and the reduction in miles per gallon continued as a linear trend with increasing ethanol content.

E.4.2 Emissions

- Regulated tailpipe emissions remained largely unaffected by the ethanol content of the fuel.
- As ethanol content increased,
  - oxides of nitrogen (NO_X), and non-methane organic gases (NMOG) showed no significant change;
  - non-methane hydrocarbons and carbon monoxide (CO) emissions dropped slightly on average, although CO did not change appreciably from E10 to E20;
  - ethanol emissions increased;
  - acetaldehyde emissions increased,
  - formaldehyde emissions increased slightly; and
  - benzene and 1,3-butadiene were expected to decrease due to dilution, but measurements were only conducted on a subset of the vehicles and have not been thoroughly analyzed to date.

E.4.3 Catalyst Temperatures

- At closed-loop operating conditions, catalyst temperatures were cooler or unchanged with higher levels of ethanol.
- Seven of the 13 tested vehicles adjusted fueling with increased ethanol content to maintain a consistent fuel:air equivalence ratio† at wide-open throttle (WOT).‡ In these cases, the catalyst temperatures at equivalent operating conditions were lower or unchanged with ethanol.
- Six of the 13 tested vehicles ran leaner§ (albeit still rich) with E20 fuel than with E0 fuel at WOT. For these vehicles catalyst temperatures were between 29°C and 35°C higher at E20 relative to E0.

---

*This result was expected because ethanol has about 67% of the energy density of gasoline on a volumetric basis.

†Equivalence ratio is a measure of the actual fuel to air (oxidizer) compared to stoichiometric conditions. "Stoichiometric" is the condition in which 100% of both fuel and air are consumed in the combustion reaction, resulting in no excess oxygen or unburned fuel.

‡Wide-open throttle (WOT) is the full power condition for spark-ignition engines and is often an open-loop condition.

§"Lean" refers to a condition in which 100% of the fuel is consumed, but excess oxygen remains after the reaction. "Rich" refers to a condition where 100% of the air is consumed, but excess unburned fuel remains after combustion.

E.4.4 Operability

Although formal driveability testing wasn't conducted during the testing reported here, no operability or driveability issues were identified using any of the ethanol blends during the limited time of the project. Each vehicle accumulated at least 100 miles on each ethanol blend, and at least 200 miles on gasoline (E0 fuel). Mileage accumulations for the vehicles ranged from 500–1,200 due to additional tests on some of the vehicles. The following observations were noted during the limited test period.

- None of the vehicles displayed a malfunction indicator light (MIL) as a result of the ethanol content of the fuel.
- No fuel filter plugging symptoms were observed.
- No cold start problems were observed in 75°F and 50°F laboratory conditions.
- No fuel leaks or conspicuous degradation of the fuel systems were observed.

E.5 SUMMARY OF SMALL NON-ROAD ENGINE TESTS AND DATA

Millions of SNREs are sold each year, including leaf blowers and line trimmers, lawn mowers, generator sets, and small tractors (all under 25 hp). EPA certifies on the order of 900 engine emission "families" for SNREs each year. Unlike the engines in modern light-duty vehicles, SNREs are typically open-loop engines—that is, these engines do not have exhaust oxygen sensing capabilities and therefore cannot compensate for ethanol content in the fuel. These open-loop engines are commonly air-cooled, and they customarily operate fuel-rich to achieve cooler combustion temperatures for longevity purposes. With a fixed fueling calibration, as ethanol content in the fuel increases, combustion becomes leaner, leading to higher combustion temperatures and higher component temperatures, as well as changes in emissions and sometimes idle speed.

Initial tests conducted by ORNL and NREL focused on identifying emissions or operational issues and measurement of several key engine temperatures with federal certification gasoline (E0) and three splash-blended fuels (E10, E15, and E20). One copy of each engine was tested on all four fuels in this pilot study.

In addition to the ORNL and NREL tests, DOE funded the Transportation Research Center (TRC) through an ORNL subcontract to test four copies of several small engines to full useful life (full life). All of these engines were tested on E0 and then aged on a dedicated fuel—E0, E10, E15, or E20. The tests performed at TRC measured emissions and temperatures at various stages of the engines' lives—when new, at half life, and at full life. The primary focus of these tests was to assess any operational problems during aging to full life and to evaluate how engine operation and emissions change over time with exposure to various levels of ethanol.

Similar to the vehicle tests, splash-blended fuels were used in this study instead of match-blended fuels—that is, the E0 fuel was simply diluted with appropriate amounts of ethanol. Similar to the vehicle results, the different fuel characteristics of match-blended and splash-blended fuels were not expected to have significant impact on temperature. Additionally, the emission results for the SNRE testing are not expected to vary significantly between splash-blended and match-blended fuels because a cold start and warm up was not included in the testing.

E.5.1 Emissions

Results from the tests of 28 SNREs generally indicated that as ethanol content increased to as much as 20%, open loop engines operated leaner with increasing ethanol. Effects of this enleanment* on emissions included the following.

- NO_X emissions increased.
- HC emissions generally decreased.
- Regulated emissions—combined HC + NO_X—decreased in most cases.
- CO emissions decreased.

E.5.2 Performance and Operability

Performance varied considerably among the engines tested, regardless of the fuel used. Therefore, it is not possible to completely isolate the effects of ethanol on operability. However, a few observations are noteworthy.

- With greater ethanol content, temperatures of the exhaust components, cylinder head, and cylinders generally increased. The largest increases were in exhaust temperature, rising between 10°C to 50°C from E0 to E15 and between 20°C to 70°C from E0 to E20. For the six engines in the pilot study in which temperatures were measured on all four fuels for each engine, temperature increases from E10 to E15 ranged between 5°C to 10°C.
- With greater ethanol content, three handheld trimmers demonstrated higher idle speed and experienced unintentional clutch engagement. The increased speed was again caused by the fuel:air mixture enleanment which can be adjusted and mitigated in some engines.
- Residential and Commercial Class I and Class IV engines were aged to full life. The residential Class I as well as the commercial engines exhibited no sensitivity to ethanol from a durability perspective. The effect of ethanol on the durability of the residential Class IV engines was not clear given that a number of these engines failed during full-life aging regardless of fuel type.
- Although not specifically characterized, no obvious materials compatibility issues were noted during the limited duration of this program.
- In the case of the 2-cylinder engine tested, temperatures and emissions varied from cylinder-to-cylinder due to differences in the air-fuel distribution between cylinders. Given this observation, multicylinder open-loop engines may prove to be more sensitive to ethanol blends.

---

*Enleanment means moving toward a leaner fuel : air equivalence ratio. In this case, from a rich condition to a leaner (albeit still rich) fuel : air equivalence ratio.

4. NEXT STEPS

Given the importance of expanding the nation's use of renewable fuels and the new renewable fuel mandate set forth in the Energy and Independence Act of 2007, DOE and others recognize the need to consider a variety of means for bringing such fuels to market. While ethanol is the most widely used renewable fuel in the United States, the E10 market—which takes up the vast majority of ethanol used today—will be saturated within a few years. Given that reality, DOE is working to expand the distribution and use of E85 and simultaneously investigate the potential of using intermediate ethanol blends (e.g., E15, E20) in conventional vehicles and engines.

This report summarizes findings to date from DOE's first phase of intermediate ethanol blends testing on vehicles and other engines. Recognizing the need for a wide range of additional tests, DOE is sponsoring a number of other studies on vehicles as well as other engines. The studies, some of which are being conducted in partnership with other organizations, are summarized in Table 4.1, with more detailed descriptions provided in the following text. Additional studies may be conducted as needed subject to available funding.

4.1 EMISSIONS AND CATALYST TEMPERATURE

Testing of the three remaining vehicles from this study is still underway; results from these tests will be presented in a second report expected in January 2009.

4.2 EMISSIONS OF VARIOUS GASOLINES AND ETHANOL BLENDS

This task, performed in collaboration with EPA and CRC, will assess the impacts of varying Reid vapor pressure (RVP), T50, T90, and aromatic content of gasoline and different ethanol/gasoline fuel blends on tailpipe emissions and performance of 19 new and 3 in-use vehicles. About 30 different match-blended fuels will be used to collect emissions data on criteria pollutants [HC, CO, NO_X, and particulate matter (PM)], ethanol, and carbonyl compounds. Cofunding from CRC will support blending and testing of two of the fuels. Detailed HC speciation data will be collected for all vehicles tested in this task. Detailed PM and semivolatile organic compound data will be collected for a subset of the fuels.

4.3 EVAPORATIVE EMISSIONS

This study, being conducted in collaboration with CRC (Project E-77), will measure evaporative emissions associated with testing gasoline fuels of varying RVP (volatility) and ethanol blends on eight vehicles. Five fuels with defined vapor pressures and ethanol content ranging from 0 to 20% will be tested on four Tier-2 near-zero low-emission vehicles and four "enhanced" 1996–2001 model year vehicles. Static permeation, running loss, hot soak, and diurnal emissions will be measured.

4.4 CATALYST DURABILITY

This task, conducted in collaboration with CRC (Project E-87), will assess the impact of intermediate ethanol blends on the full useful life of the catalyst system. In Phase I, the study will initially screen 25 vehicles for catalyst performance and key temperatures during open-loop (WOT) operation. Full-life (120,000 miles) studies on about 10 engine families will follow in Phase II. For each engine family, eight vehicles will be tested—with a pair dedicated to one of four fuels ranging from E0 to E20. A total of 80 vehicles will be tested (10 models × 4 fuel types × 2 vehicles per pair). Engines will have compression and leakdown checks performed at each emissions testing interval. Any operational issues observed will also be reported.

Table 4.1. Summary of DOE intermediate ethanol blends programs

Intermediate blends test	Scope of project	Test labs	Status
Programs covered in the report			
Vehicle emissions and catalyst temperature	Focus on regulated tailpipe emissions, exhaust and catalyst temperatures, and short-term operational issues. A total of 16 late model vehicles are in the study.	ORNL, TRC, NREL/CDPHE (Colorado Department of Public Health—Aurora Emissions Technical Center)	Data for 13 vehicles at 75°F are provided in this report. Data from remaining 3 vehicles and 50°F testing expected in January 2009.
Small non-road engines—emissions, temperatures, full, useful life (full life)	Focus on emissions, operating temperatures, performance issues. 28 engines tested; 17 of these engines operated to full life with emissions monitoring.	ORNL, NREL, TRC	Completed.
Ongoing and future testing			
Vehicle emissions with various gasolines and ethanol blends	Focus on the effect of various fuel characteristics on tailpipe emissions. Cosponsored by EPA as part of its EPAct Program to revise the Complex Model. 22 vehicles and 30+ different fuels are in the study.	Southwest Research Institute (SwRI)	Phase I complete. Phase II In progress.
Evaporative emissions	Focus on evaporative emissions and permeation. Collaboration with CRC Project E-77. Managed by Harold Haskew & Associates. 10 vehicles are in the study.	ATL	In progress.
Catalyst durability	Focus on long-term catalyst durability. Collaboration with CRC Project E-87. Phase I: Initially screening 25 vehicles (CRC). Phase II: Testing and aging of up to 80 vehicles (ORNL/CRC).	 TRC SwRI	In progress.
Driveability	Focus on driveability issues, including cold start. Collaboration with CRC Project CM-138. Six non-FFVs are in the study; further studies including high ambient temperature and high altitude are planned.	Yakima, Washington, test track	Testing completed; analysis underway and CRC report is expected November 2008.
Fuel system materials compatibility	Focus on fuel systems components compatibility. Collaboration with CRC Project AVFL-15.	TRC	In progress.
Specialty engines	Snowmobiles, motorcycles, marine, ATVs, other.	TBD	Test plans under development.

4.5 DRIVEABILITY

This task, conducted in collaboration with CRC (Project CM-138), evaluates impacts of intermediate blends on the driveability of six late-model non-FFVs and of various E85 fuels in 20 FFVs. The standard driveability test, developed by CRC, was used. Fuels tested in the study include E0, E15, and E20 with prescribed vapor pressures.

4.6 FUEL SYSTEM MATERIALS COMPATIBILITY

This task, conducted in collaboration with CRC (Project AVFL-15), will evaluate the durability of wetted components of fuel systems in non-FFVs when exposed to E10 and E20. This study will measure effects on all materials found in the fuel system, including plastics, elastomers, O-rings, and hose materials.

4.7 SPECIALTY ENGINES

This task will consider the effects of intermediate ethanol blends on various other non-automotive engine types (e.g., marine, motorcycles, snowmobiles). Preliminary planning meetings have been held with industry representatives to guide the development of test plans for these engines.

4.8 FUTURE REPORTS

As results from these studies become available, DOE will issue additional reports with analyses as well as core data.

DOE will continue to work closely with EPA, industry partners, and others to ensure that testing is sound and targeted at providing data needed to assess the effects of intermediate ethanol blends on conventional vehicles as well as other engines.